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Kim et al.

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(54) **APPARATUS AND METHOD FOR DECODING SPACE-TIME BLOCK CODED (STBC) SIGNAL**

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(73) Assignee: **Samsung Electronics Co., Ltd.**, Suwon-si (KR)

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(22) Filed: **Sep. 28, 2007**

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(30) **Foreign Application Priority Data**

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(51) **Int. Cl.**
H04L 27/06 (2006.01)

(52) **U.S. Cl.** **375/341**; 375/260; 375/262; 375/267; 375/340; 714/794

(58) **Field of Classification Search** 375/340–341, 375/260, 262, 267, 347; 714/794
See application file for complete search history.

(56) **References Cited**

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(57) **ABSTRACT**

Apparatus and method for decoding a Space-Time Block Coded (STBC) signal. The decoding apparatus includes a channel estimator for estimating a real equivalent channel based on a coded signal; a channel converter for decomposing the real equivalent channel to a unit matrix and a subchannel; a receive signal converter for converting the coded signal to a real equivalent receive signal and converting the real equivalent receive signal to a converted receive signal based on the unit matrix; and a detector for detecting an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel. Since the transmit signal candidates are independent of each other, the complexity of the maximum likelihood decoding can be decreased. With the lowered complexity of the receiver, the power consumption for the decoding can be reduced and the high-speed data can be transmitted more easily in the actual mobile communication environment.

16 Claims, 6 Drawing Sheets

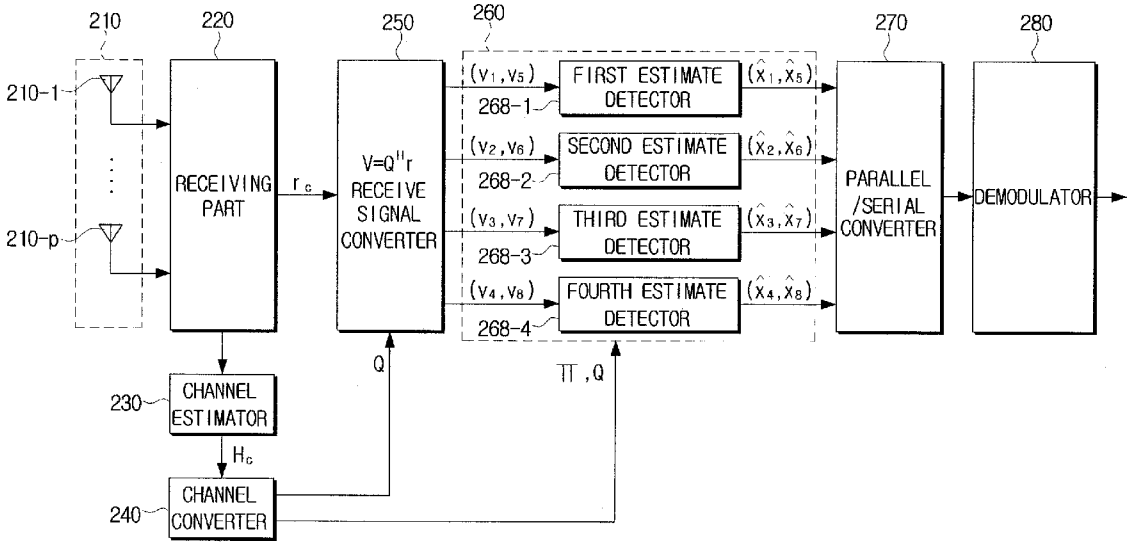


FIG. 1

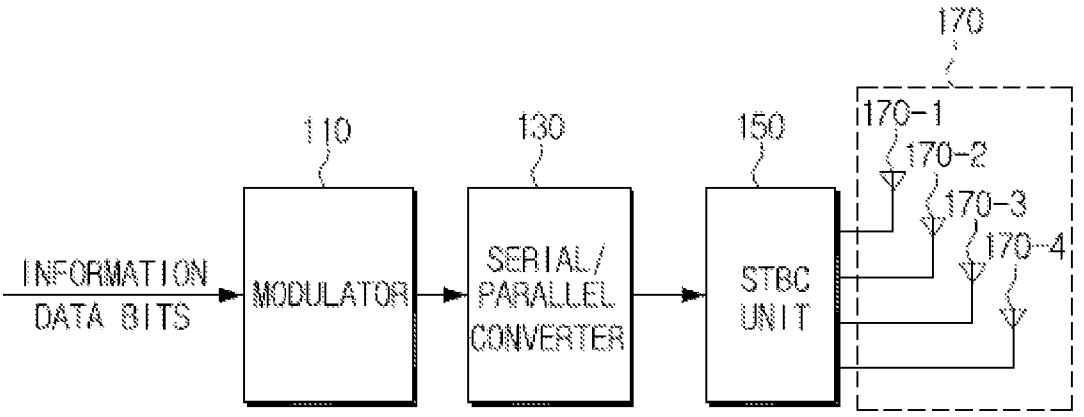

170
110
130
150
170-1
170-2
170-3
170-4
INFORMATION DATA BITS
MODULATOR
SERIAL/ PARALLEL CONVERTER
STBC UNIT

FIG. 2

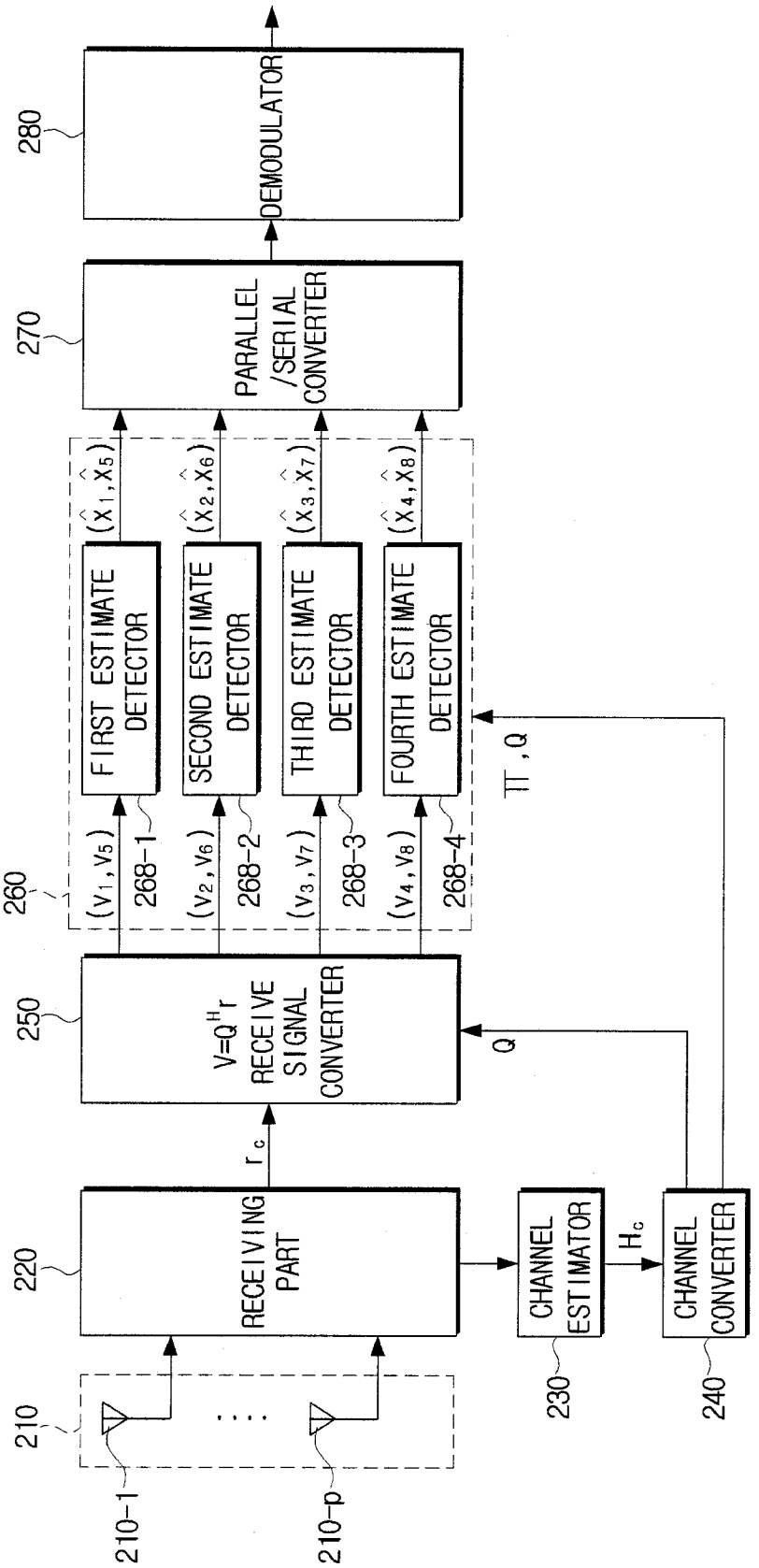

280
DEMODULATOR
270
PARALLEL /SERIAL CONVERTER
260
FIRST ESTIMATE DETECTOR
SECOND ESTIMATE DETECTOR
THIRD ESTIMATE DETECTOR
FOURTH ESTIMATE DETECTOR
268-1
268-2
268-3
268-4
250
V=Q^H r
RECEIVE SIGNAL CONVERTER
220
RECEIVING PART
210
210-1
210-p
230
CHANNEL ESTIMATOR
240
CHANNEL CONVERTER
r_c
H_c
Q
TT , Q

FIG. 3

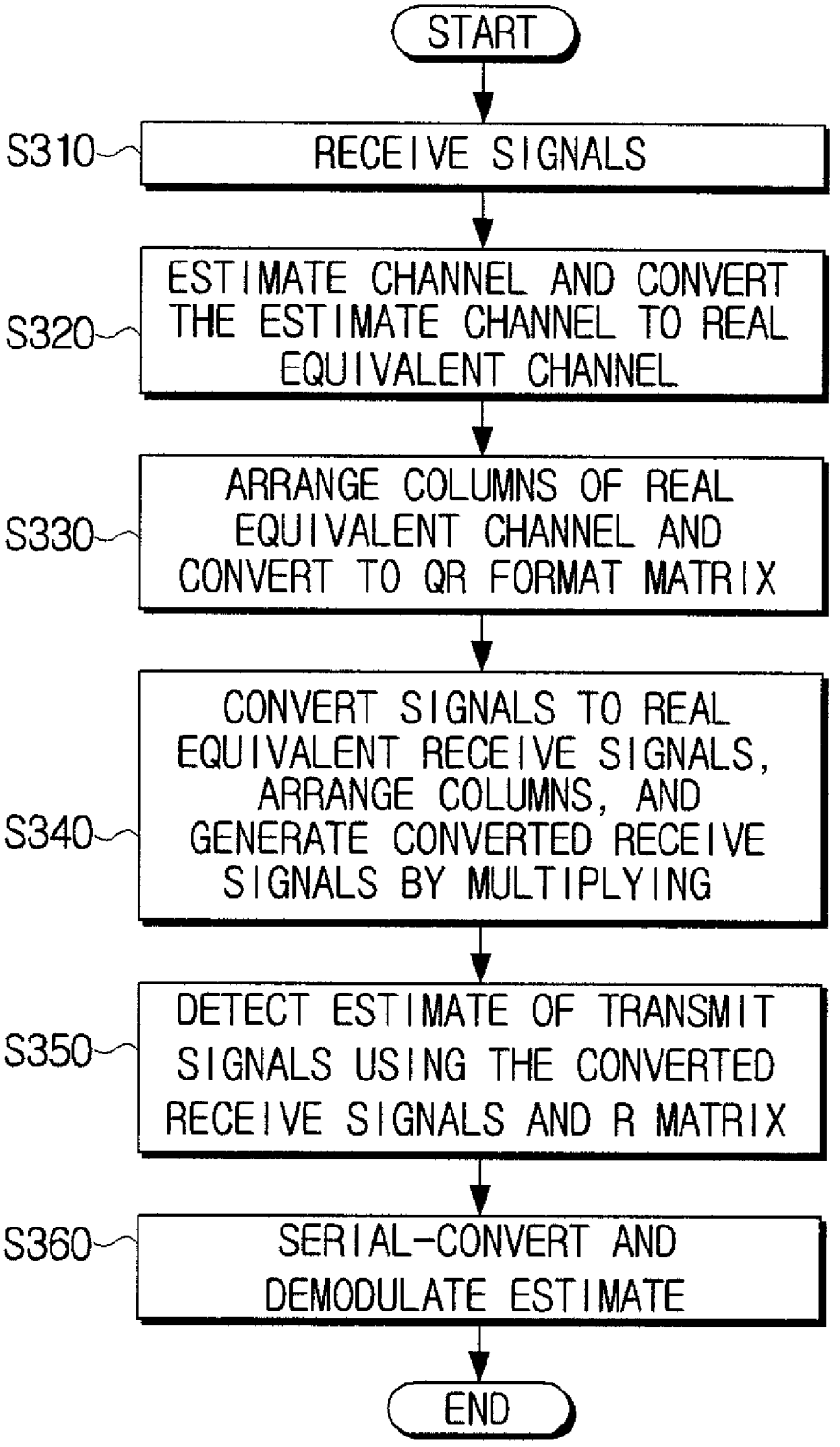

START
S310
RECEIVE SIGNALS
S320
ESTIMATE CHANNEL AND CONVERT THE ESTIMATE CHANNEL TO REAL EQUIVALENT CHANNEL
S330
ARRANGE COLUMNS OF REAL EQUIVALENT CHANNEL AND CONVERT TO QR FORMAT MATRIX
S340
CONVERT SIGNALS TO REAL EQUIVALENT RECEIVE SIGNALS, ARRANGE COLUMNS, AND GENERATE CONVERTED RECEIVE SIGNALS BY MULTIPLYING
S350
DETECT ESTIMATE OF TRANSMIT SIGNALS USING THE CONVERTED RECEIVE SIGNALS AND R MATRIX
S360
SERIAL-CONVERT AND DEMODULATE ESTIMATE
END

FIG. 4

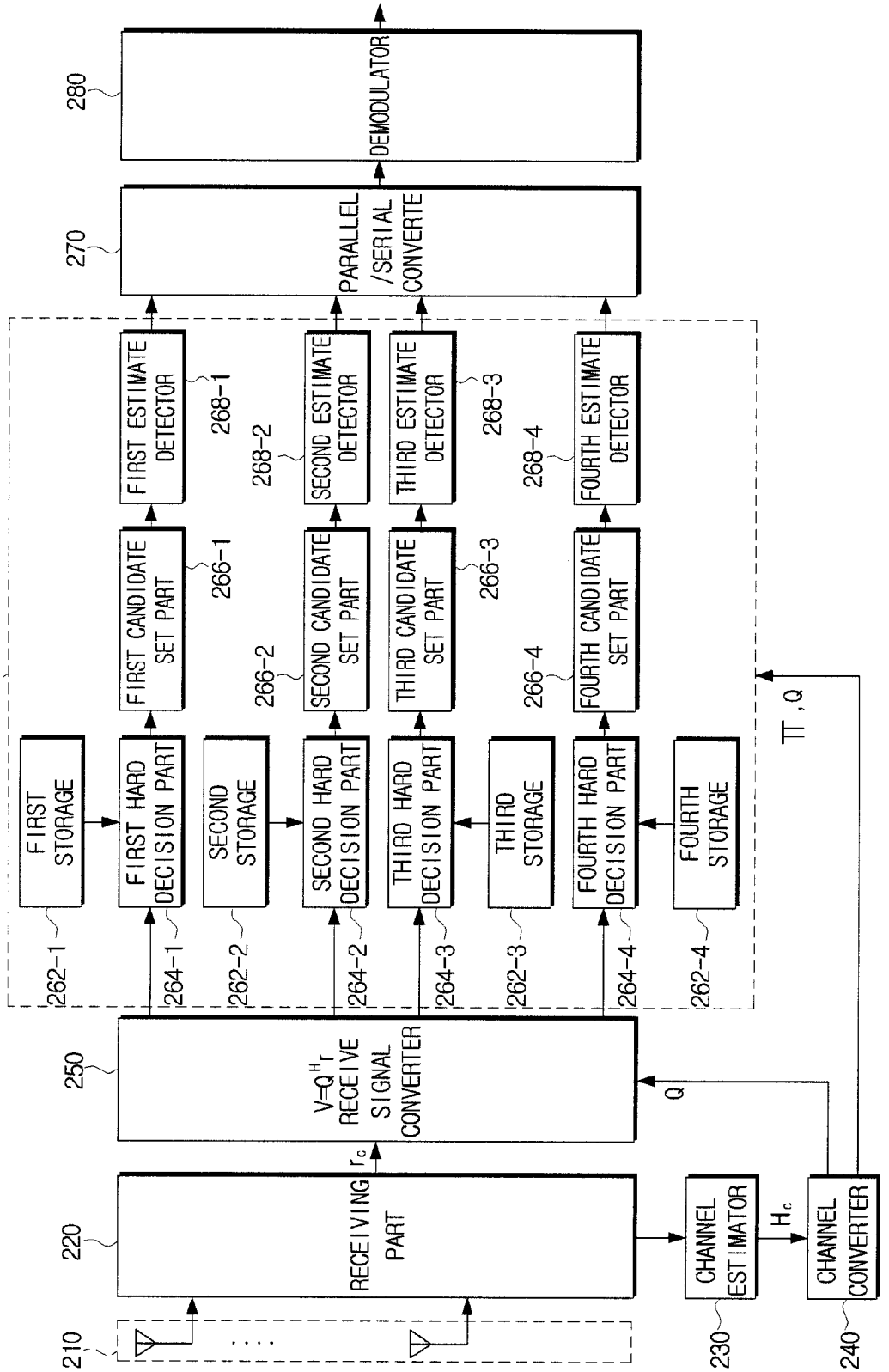

280
DEMODULATOR
270
PARALLEL /SERIAL CONVERTE
260
FIRST ESTIMATE DETECTOR
268-1
SECOND ESTIMATE DETECTOR
268-2
THIRD ESTIMATE DETECTOR
268-3
FOURTH ESTIMATE DETECTOR
268-4
FIRST CANDIDATE SET PART
266-1
SECOND CANDIDATE SET PART
266-2
THIRD CANDIDATE SET PART
266-3
FOURTH CANDIDATE SET PART
266-4
FIRST STORAGE
FIRST HARD DECISION PART
SECOND STORAGE
SECOND HARD DECISION PART
THIRD HARD DECISION PART
THIRD STORAGE
FOURTH HARD DECISION PART
FOURTH STORAGE
262-1
264-1
262-2
264-2
264-3
262-3
264-4
262-4
TT , Q
250
V=Q^H r
RECEIVE SIGNAL CONVERTER
Q
r_c
220
RECEIVING PART
CHANNEL ESTIMATOR
H_c
CHANNEL CONVERTER
210
230
240

FIG. 5

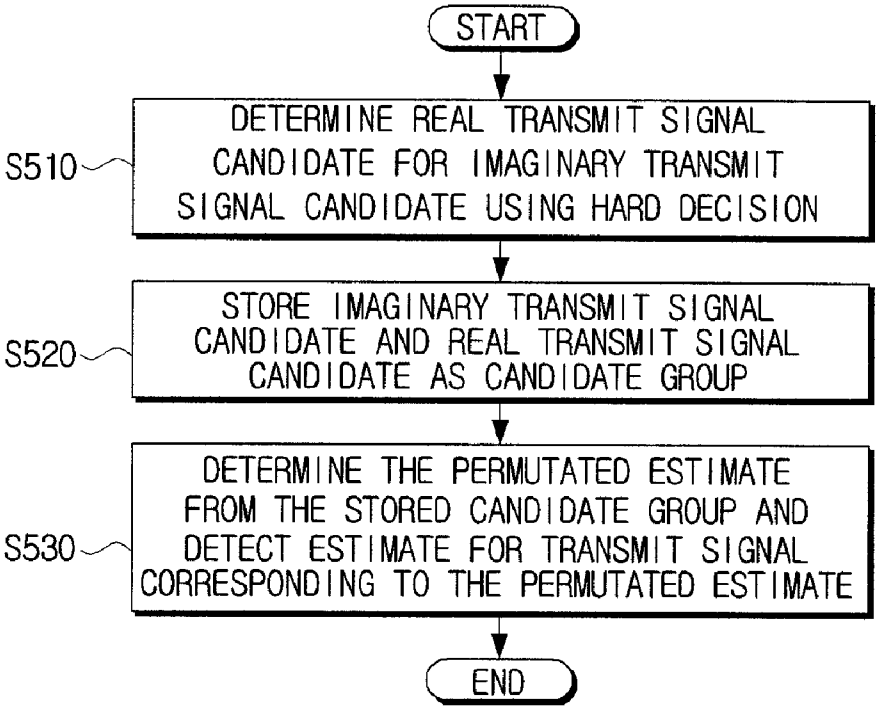
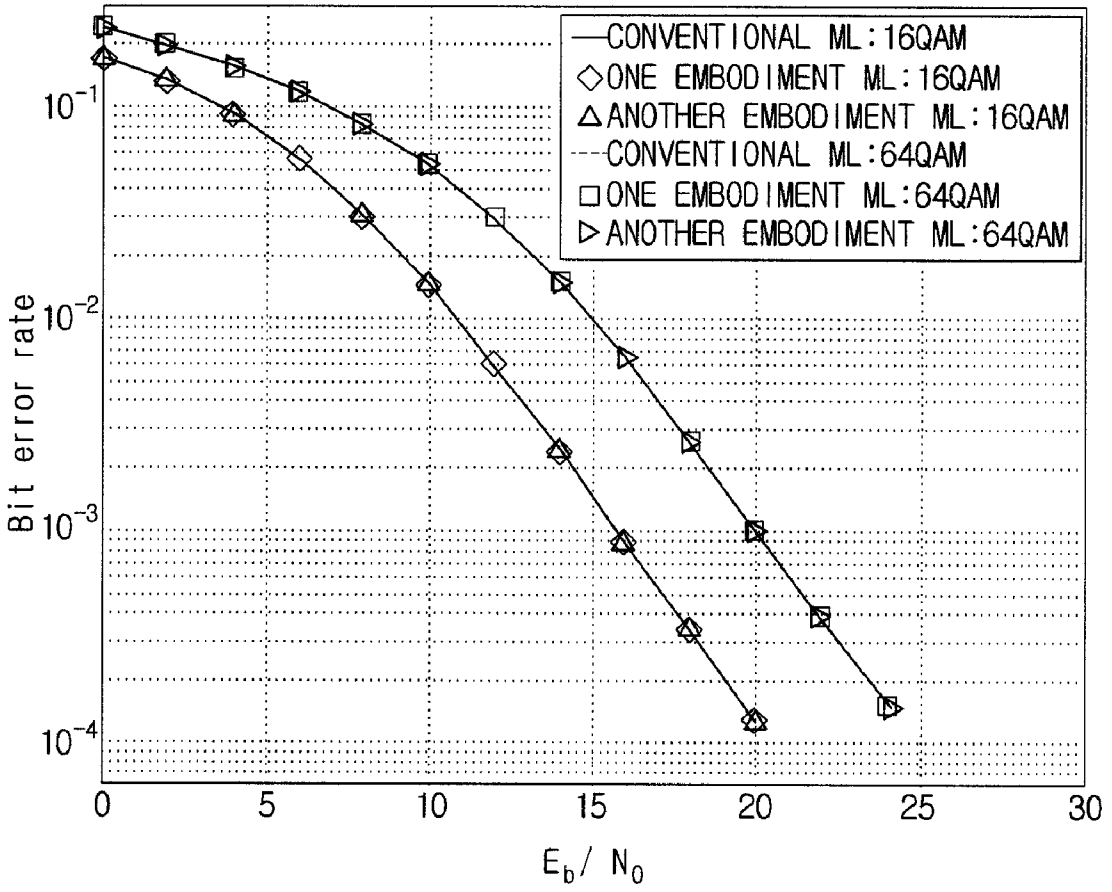


FIG. 6

RECEIVER	COMPLEXITY
CONVENTIONAL	$32\ \|\Omega\|^2 C_M + 48\ \|\Omega\|^2 C_A$
ONE EMBODIMENT	$(20\ \|\Omega\| + 64) C_M + (16\ \|\Omega\| + 56)\ C_A$
ANOTHER EMBODIMENT	$(24\sqrt{\|\Omega\|} + 64) C_M + (16\sqrt{\|\Omega\|} + 56)\ C_A$

FIG. 7


CONVENTIONAL ML:16QAM
ONE EMBODIMENT ML:16QAM
ANOTHER EMBODIMENT ML:16QAM
CONVENTIONAL ML:64QAM
ONE EMBODIMENT ML:64QAM
ANOTHER EMBODIMENT ML:64QAM
Bit error rate
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
E_b / N_0

APPARATUS AND METHOD FOR DECODING SPACE-TIME BLOCK CODED (STBC) SIGNAL

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. §119 from Korean Patent Application No. 10-2007-0050856, filed on May 25, 2007, in the Korean Intellectual Property Office, the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to a communication apparatus and a control method thereof More particularly, the present invention relates to an apparatus for decoding a space-time block coded (STBC) signal and a control method thereof.

2. Description of the Related Art

Mobile communication systems are advancing to wireless data packet communication systems of high speed and high quality to provide data service and multimedia service over CDMA 2000 1x networks beyond voice oriented service provided over the conventional IS-95A and IS-95B networks. 3rd-generation (3G) mobile communication systems discussed as the wireless data packet communication systems comprise High Speed Downlink Packet Access (HSDPA) based on 3GPP and 1xEVDV system based on 3GPP2. The 3G mobile communication system enables to transmit radio packet data of high speed and high quality over 2 Mbps. Further, a 4G mobile communication system is under development to provide very high speed and high quality multimedia service over Internet Protocol (IP) network.

Since the high speed packet data service provides multimedia contents to a mobile terminal, a downlink capacity from a base station to the mobile terminal needs to increase. To increase the downlink capacity, more base stations can be installed or the frequency band can be extended. However, the base station installation requires much cost and the frequency band extension is subject to practical limitations. Instead, 3GPP/3GPP2 employs an array antenna to standardize a multiple antenna technique for enhancing the system throughput and the transmission capability of the base station.

The multiple antenna technique can provide transmit diversity and mitigate the multipath fading occurring in the downlink radio channel. Representative transmit diversity techniques comprise a Selective Transmit Diversity (STD), Space Time Spreading (STS), Space-Time Block Coding (STBC), and so forth. The transmit diversity techniques can be divided to an open-loop scheme which requires no feedback information and a closed-loop scheme which requires feedback information based on whether the feedback information including channel information is transmitted from a receiver to a transmitter.

The STD adopts the closed-loop scheme, and the STS and the STBC adopt the open-loop scheme. In general, the transmit diversity requiring the feedback information is subject to the degradation of the system throughput because of the transfer delay and the transfer error of the feedback information. Hence, it is difficult to apply the transmit diversity in a radio environment where the mobile terminal travels quite fast. The transmit diversity techniques can be classified to an antenna space technology. In the antenna space technology, the transmitter transmits signals over the individual transmit antenna and the receiver estimates the multipath fading channel from the individual transmit antenna and acquires a diversity gain by processing the signals received from the transmit antennas.

A representative adaptive antenna system using the antenna space technology is a Multiple Input Multiple Output (MIMO) system. Since the MIMO system spatial-multiplexes and transfers data, the communication system throughput can be greatly enhanced. On the assumption that the receiver can acquire the channel information, the MIMO system achieves a high data rate and a low bit error probability.

Particularly, a quasi-orthogonal STBC scheme is the transmission of transmission rate '1'. The receiver uses a maximum likelihood detection to decode the quasi-orthogonal STBC scheme. Disadvantageously, the maximum likelihood detection suffers high complexity.

SUMMARY OF THE INVENTION

Exemplary embodiments of the present invention address at least the above problems and/or disadvantages and other disadvantages not described above. Also, the present invention is not required to overcome the disadvantages described above, and an exemplary embodiment of the present invention may not overcome any of the problems described above.

The present invention provides an apparatus for decoding with low complexity and a control method thereof.

According to an aspect of the present invention, there is provided a decoding apparatus which comprises a channel estimator for estimating a real equivalent channel based on a coded signal; a channel converter for decomposing the real equivalent channel to a unit matrix and a subchannel; a receive signal converter for converting the coded signal to a real equivalent receive signal and converting the real equivalent receive signal to a converted receive signal based on the unit matrix; and a detector for detecting an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel.

The coded signal may be encoded using a quasi-orthogonal space-time block code.

The detector may comprise a hard decision part for determining a transmit signal candidate group using a hard decision; and an estimate detector for detecting a transmit signal estimate from the transmit signal candidate group output from the hard decision part by performing the maximum likelihood decoding.

The hard decision part may determine a real transmit signal candidate as the transmit signal candidate group from an imaginary transmit signal candidate using the hard decision.

The channel converter may rearrange columns of a real equivalent channel using an orthogonal matrix and convert the rearranged real equivalent channel to the unit matrix and the subchannel.

The coded signal may be transmitted over four transmit antennas.

The channel converter may convert the real equivalent channel to the unit matrix and the subchannel using a modified Gram-Schmidt (MGS).

The subchannel may be of an upper triangular matrix format.

The detector may detect the estimate corresponding to the transmit signal by independently decoding the converted receive signal corresponding to the coded signal.

According to the aspect of the present invention, a decoding method comprises estimating a real equivalent channel based on a coded signal; decomposing the real equivalent

channel to a unit matrix and a subchannel; converting the coded signal to a real equivalent receive signal and converting the real equivalent receive signal to a converted receive signal based on the unit matrix; and detecting an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel.

The coded signal may be encoded using a quasi-orthogonal space-time block code.

The estimate detecting operation may comprise determining a transmit signal candidate group using a hard decision; and detecting a transmit signal estimate from the transmit signal candidate group by performing the maximum likelihood decoding.

The candidate group determining operation may determine a real transmit signal candidate as the transmit signal candidate group from an imaginary transmit signal candidate using the hard decision.

The channel decomposing operation may rearrange columns of a real equivalent channel using an orthogonal matrix and converts the rearranged real equivalent channel to the unit matrix and the subchannel.

The coded signal may be transmitted over four transmit antennas.

The channel converting operation may convert the real equivalent channel to the unit matrix and the subchannel using a modified Gram-Schmidt (MGS).

The subchannel may be of an upper triangular matrix format.

The estimate detecting operation may detect the estimate corresponding to the transmit signal by independently decoding the converted receive signal corresponding to the coded signal.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

The above and/or other aspects of the present invention will be more apparent by describing certain exemplary embodiments of the present invention with reference to the accompanying drawings, in which:

FIG. **1** is a diagram of a transmitter of a MIMO mobile communication system by using four transmit antennas and adopting a STBC scheme;

FIG. **2** is a block diagram of a receiver corresponding to the transmitter of FIG. **1** according to one exemplary embodiment of the present invention;

FIG. **3** is a flowchart of a signal demodulating method of the receiver of FIG. **2**;

FIG. **4** is a block diagram of a receiver using hard decision according to another exemplary embodiment of the present invention;

FIG. **5** is a flowchart of a maximum likelihood decoding method using the hard decision at the detector of FIG. **4**;

FIG. **6** is a table showing the complexity of the conventional decoding method and the exemplary embodiments of the present invention; and

FIG. **7** is a graph showing the bit error rate of the conventional decoding method and the present decoding method.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

Certain exemplary embodiments of the present invention will now be described in greater detail with reference to the accompanying drawings.

In the following description, same drawing reference numerals are used for the same elements even in different drawings. The matters defined in the description, such as detailed construction and elements, are provided to assist in a comprehensive understanding of the invention. Thus, it is apparent that the present invention can be carried out without those specifically defined matters. Also, well-known functions or constructions are not described in detail since they would obscure the invention with unnecessary detail.

FIG. **1** is a diagram of a transmitter structure of a MIMO mobile communication system by using four transmit antennas and adopting a STBC scheme.

The transmitter of FIG. **1** comprises a modulator **110**, a serial/parallel converter **130**, a Space-Time Block Code (STBC) unit **150**, and four transmit antennas **170**; that is, a first transmit antenna **170-1** through a fourth transmit antennas **1704**.

The modulator **110** generates modulation symbols by modulating information data bits input with a preset modulation scheme upon receiving the information data bits, and outputs the generated modulation symbols to the serial/parallel converter **130**. The modulation scheme can employ one of Binary Phase Shift Keying (BPSK) scheme, Quadrature Phase Shift Keying (QPSK) scheme, Quadrature Amplitude Modulation (QAM) scheme, Pulse Amplitude Modulation (PAM) scheme, and Phase Shift Keying (PSK) scheme.

The serial/parallel converter **130** receives and parallel-converts the serial modulation symbols fed from the modulator **110** and outputs the parallel modulation symbols to the STBC unit **150**. Herein, it is assumed that the serial modulation symbols output from the modulator **110** is $s_1 s_2 s_3 s_4$. The STBC unit **150** performs the quasi-orthogonal STBC to the four modulation symbols; that is, to $s_1 s_2 s_3 s_4$ fed from the serial/parallel converter **130** and produces a transmit signal s as expressed in Equation 1.

$$s = \begin{bmatrix} s_1 & -s_2^* & s_3 & -s_4^* \\ s_2 & s_1^* & s_4 & s_3^* \\ s_3 & -s_4^* & s_1 & -s_2^* \\ s_4 & s_3^* & s_2 & s_1^* \end{bmatrix} \quad \text{[Equation 1]}$$

s is a typical T×N matrix. In this exemplary embodiment of the present invention, since the block size of the STBC unit **150** is T=4 and the number of the transmit antennas is N=4, s is 4×4 matrix.

In the matrix of Equation 1, the elements of the row correspond to the modulation symbols transmitted on the transmit antennas **170** in a specific time interval, and the elements of the column correspond to the modulation symbols transmitted on a specific transmit antenna **170** in a unit time interval.

Specifically, in the first time interval, the first transmit antenna **170-1** sends s_1, the second transmit antenna **170-2** sends $-s^*_2$, the third transmit antenna **170-3** sends s_3, and the fourth transmit antenna **1704** sends $-s^*_4$. Likewise, in the fourth time interval, the first transmit antenna **170-1** sends s_4, the second transmit antenna **170-2** sends s^*_3, the third transmit antenna **170-3** sends s_2, and the fourth transmit antenna **170-4** sends s^*_1.

As expressed in Equation 1, the STBC unit **150** controls to transmit the modulation symbols on the four transmit antennas **170** in the four time intervals by applying the negative operation and the conjugate operation to the input modulation symbols.

Now, a receiver structure corresponding to the transmitter structure of FIG. **1** is described by referring to FIG. **2**.

FIG. **2** is a block diagram of the receiver corresponding to the transmitter of FIG. **1** according to one exemplary embodiment of the present invention.

The receiver of FIG. **2** comprises a plurality of receive antennas **210**, e.g., P-ary receive antennas **210**; a first receive antenna **210-1** through a P-th receive antenna **210-***p*, a receiving part **220**, a channel estimator **230**, a channel converter **240**, a receive signal converter **250**, a detector **260**, a parallel/serial converter **270**, and a demodulator **280**. While it is assumed that the number of the transmit antennas **170** of the transmitter is different from the number of the receive antennas **210** of the receiver of FIG. **2**, the number of the transmit antennas **170** of the transmitter may be equal to the number of the receive antennas **210** of the receiver.

As described earlier in FIG. **1**, the signals transmitted over the four transmit antennas **170** of the transmitter are received at the first receive antenna **210-1** through the P-th receive antenna **210-***p* respectively.

The receiving part **220** provides the receive signal r_c attained at the first receive antenna **210-1** through the P-th receive antenna **210-***p* to the channel estimator **230** and the receive signal converter **250**.

To ease the understanding of the present invention, when the signals are transmitted to four receive antennas **210**, the data received at the first receive antenna **210-1** is decoded, which is described.

The receive signal r_c received at the receiver is expressed as Equation 2 by multiplying a transmit channel H_c by the transmit signal s and adding noise n.

$$r_c = H_c s + n \quad \text{[Equation 2]}$$

An estimate $\hat{s}$ for the transmit signal s detected at the detector **260** satisfies Equation 3.

$$\hat{s} = \arg\min \|r - H_c s\| \quad \text{[Equation 3]}$$

The channel estimator **230** generates a channel matrix H_c as expressed in Equation 4 by estimating channel coefficients h which represent the channel gain of the receive signals received on the receive antennas **210** respectively.

$$H_c = \begin{bmatrix} h_1 & h_2 & h_3 & h_4 \\ h_2^* & -h_1^* & h_4^* & -h_3^* \\ h_3 & h_4 & h_1 & h_2 \\ h_4^* & -h_3^* & h_2^* & -h_1^* \end{bmatrix} \quad \text{[Equation 4]}$$

h_i, which is a zero-mean independent complex Gaussian random variable, is a channel gain of receiving the receive signal on the i-th antenna.

The channel estimator **230** converts the channel matrix H_c to a real equivalent channel as expressed in Equation 5.

$$H = \begin{bmatrix} \mathrm{Re}\{H_c\} & -\mathrm{Im}\{H_c\} \\ \mathrm{Im}\{H_c\} & \mathrm{Re}\{H_c\} \end{bmatrix} \quad \text{[Equation 5]}$$

While the columns of the complex channel H_c may not be orthogonal, the real column and the imaginary column of the real equivalent channel are orthogonal each other. The real equivalent channel becomes 8×8 matrix.

In the mean time, to detect the transmit signal using the real equivalent channel the receive signal r_c is converted to a real equivalent receive signal r as expressed in Equation 6.

$$r = [Re\{r_c\} Im\{r_c\}]^T \quad \text{[Equation 6]}$$

The transmit signal candidate s is also converted to a real equivalent transmit signal candidate x as expressed in Equation 7.

$$x = [Re\{s\} Im\{s\}]^T \quad \text{[Equation 7]}$$

The channel converter **240** rearranges the columns of the real equivalent channel H to decompose the real equivalent channel H to a matrix of the simplified QR format. To rearrange the real equivalent channel H, the channel converter **240** generates a channel H_{perm}=Πs permutated by multiplying the matrix Π of Equation 8 by the real equivalent channel H.

Next, to make the permutated channel H_{perm} meet Equation 2, the channel converter **240** applies the matrix Π required to rearrange the columns of the real equivalent channel H to the detector **260**. Hence, the detector **260** generates the permutated transmit signal x_{perm}=Πx by multiplying the real equivalent transmit signal s by the matrix Π.

$$\Pi = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{[Equation 8]}$$

Accordingly, the real equivalent receive signal r can be expressed as Equation 9 by multiplying the permutated channel H_{perm} by the permutated transmit signal x_{perm} and adding the noise n.

$$r = H_{perm} x_{perm} + n \quad \text{[Equation 9]}$$

Note that the noise n in Equation 9 is also the real equivalent noise.

The channel converter **240** decomposes the permutated channel H_{perm} to QR using the modified Gram-Schmidt (MGS). In doing so, Q is a unit matrix 8×8. R, which is the subchannel of the permutated channel, is a 8×8 upper triangular format matrix expressed as Equation 10.

$$R = \begin{bmatrix} r_{11} & 0 & 0 & 0 & r_{15} & 0 & 0 & 0 \\ 0 & r_{22} & 0 & 0 & 0 & r_{26} & 0 & 0 \\ 0 & 0 & r_{33} & 0 & 0 & 0 & r_{37} & 0 \\ 0 & 0 & 0 & r_{44} & 0 & 0 & 0 & r_{48} \\ 0 & 0 & 0 & 0 & r_{55} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_{66} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_{77} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_{88} \end{bmatrix} \quad \text{[Equation 10]}$$

$$= \begin{bmatrix} r_{11} & 0 & 0 & 0 & r_{15} & 0 & 0 & 0 \\ 0 & r_{11} & 0 & 0 & 0 & r_{15} & 0 & 0 \\ 0 & 0 & r_{11} & 0 & 0 & 0 & r_{15} & 0 \\ 0 & 0 & 0 & r_{11} & 0 & 0 & 0 & r_{15} \\ 0 & 0 & 0 & 0 & r_{55} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_{55} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & r_{15} \end{bmatrix}$$

wherein

-continued

$$r_{11} = r_{22} = r_{33} = r_{44} = \|h_{perm1}\|,$$

$$r_{55} = r_{66} = r_{77} = r_{88} = \sqrt{h_{perm3}^H h_{perm3} + |R_{13}|^2 - (h_{perm3}^H h'_{perm1} + (h'_{perm1})^H h_{perm3})}$$

$$r_{13} = r_{26} = r_{37} = r_{48} = \frac{1}{R_{11}} h_{perm1}^H h_{perm2}$$

In Equation 10, $h_{perm\ i}$ denotes i-th row of the permutated channel H_{perm}, h_i^H denotes the Hermitian transpose of the i-th row of H_{perm}, and $\|h_i\|$ denotes the Euclidean norm of h_i. $h_{perm\ 1}'$ is $(R_{13}/R_{11})h_1$.

Accordingly, the equivalent expression by multiplying Equation 9 by Q^H is expressed as Equation 11. The detector **260** detects a signal satisfying Equation 11 among the permutated transmit signal candidates $(x_{perm\ j}, x_{perm\ j+4})(j=1, 2, 3, 4)$ as a permutated estimate $(\hat{x}_{perm\ j}, \hat{x}_{perm\ j+4})(j=1, 2, 3, 4)$

$$v = Rx_{perm} + \tilde{n} \quad \text{[Equation 11]}$$

$$\hat{x}_{perm} = \text{argmin}\|v - Rx_{perm}\|^2 = \text{argmin}\sum_{j=1}^{4} f_j \quad \text{[Equation 12]}$$

In Equations 11 and 12, $v=Q^H r$, $\tilde{n}=Q^H n$, and $f_j=|v_j - r_{11}x_{perm\ j} - r_{15}x_{perm\ j+4}|^2 + |v_{j+1} - r_{55}x_{perm\ j+4}|^2$. By taking into account the between the rows, Equation 12 can be expressed as Equation 13.

$$\hat{x}_{perm} = \text{argmin}\sum_{j=1}^{4} f_j = \sum_{j=1}^{4} \text{argmin} f_j \quad \text{[Equation 13]}$$

As one can see from Equation 13, the permutated transmit signal candidates $(x_{perm\ j}, x_{perm\ j+4})$ are independent of each other. Hence, when the detector **260** detects the estimate of the transmit signal using the maximum likelihood, the complexity is lowered.

To detect the estimate as above, the channel converter **230** applies Q to the receive signal converter **250** and applies the matrix Π and the matrix Q to the detector **260**.

The receive signal converter **250** converts the receive signal r_c provided from the receiving part **220** to the real equivalent receive signal r of Equation 6 and generates Q^H from Q provided from the channel converter **240**. Next, the receive signal converter **250** generates the receive signal $v=Q^H r$ converted by multiplying the generated Q^H by the equivalent receive signal r, and applies the converted receive signal v to the detector **260**.

The detector **260** detects an estimate of the transmit signal by performing the maximum likelihood decoding using the converted receive signal v fed from the receive signal converter **250** and the subchannel R fed from the channel converter **240**.

Since the individual permutated transmit signal candidate $(x_{perm\ j}, x_{perm\ j+4})$ is independent from the other permutated transmit signal candidates as shown in Equation 12, four estimate detectors **260** independently detect the estimate of the corresponding transmit signal in the detector **260**. Specifically, the first estimate detector **268-1** receives the converted receive signals v_1, v_5 from the receive signal converter **250**, receives r_{11}, r_{15}, r_{55} from the channel converter **240**, detects the permutated estimate $\hat{x}_{perm\ 1}$, $\hat{x}_{perm\ 5}$ meeting Equation 12 from the transmit signal candidates, and outputs the estimate $\hat{x}_1$, $\hat{x}_5$ for the transmit signal corresponding to the permutated estimate. The second estimate detector **268-2** through the fourth estimate detector **268-4** also detect the estimate of the corresponding transmit signal.

After the estimate detection as above, the first estimate detector **268-1** detects (x_1, x_5) The required maximum likelihood complexity is 0 (Ω), where Ω is the modulation order. Likewise, the maximum likelihood complexity required for the second estimate detector **268-2**, the third estimate detector **268-3**, and the fourth estimate detector **268-4** to detect the estimate is 0 (Ω) respectively. Ultimately, the maximum likelihood complexity of the detector **260** is 0 (4Ω).

In this exemplary embodiment of the present invention, the descriptions are limited to the case where the signals are transmitted over the four transmit antennas. In general, when the signals are transmitted over n-ary transmit antennas, the maximum likelihood complexity of the receiver is 0 (NΩ) which is considerably reduced compared to the conventional 0 ($\Omega^{N/2}$).

If the detector **260** knows the estimate $\hat{x}_{j+4}$ of the transmit signal x_{j+4}, the maximum likelihood complexity of the receiver can be far more lowered.

When the detector **260** knows $\hat{x}_{j+4}$, $\hat{x}_j$ is expressed as Equation 14.

$$\begin{aligned}\hat{x}_{permj} &= \text{argmin}|v_j - r_{11}x_{permj} - r_{15}x_{permj+4}|^2 + |v_{j+1} - r_{55}x_{permj+4}|^2 \\ &= \text{argmin}|\hat{v} - rx_{permj}|^2 \\ &= D(\hat{v}_j / r_{11})\end{aligned} \quad \text{[Equation 14]}$$

That is, the detector **260** can easily detect the permutated estimate $\hat{x}_{perm\ j}$ merely using the hard decision.

When $\hat{x}_{perm\ j}$ is detected, the complexity of the first estimate detector **268-1** for detecting $\hat{x}_{perm\ j}$ becomes 0 ($\Omega^{1/2}$). Thus, the maximum likelihood complexity of the detector **260** is 0 ($4\Omega^{1/2}$).

In this exemplary embodiment of the present invention, the signals are transmitted over the four transmit antennas. In general, if the signals are transmitted over n-ary transmit antennas, the maximum likelihood complexity of the receiver is 0 ($N\Omega^{N/4}$), which is considerably decreased compared to the conventional 0 ($\Omega^{N/2}$).

The parallel/serial converter **270** serial-converts the parallel modulation symbols which are the estimates output from the detector **260** and then outputs the serial modulation symbols to the demodulator **280**. The demodulator **280** receives the serial modulation symbols from the parallel/serial converter **270** and restores the original information data bits by demodulating the symbols using a demodulation scheme corresponding to the modulation scheme applied at the modulator **110** of the transmitter.

FIG. **3** is a flowchart of a signal demodulating method of the receiver of FIG. **2**.

The receiving part **220** receives the receive signals on the receive antennas **210** and applies the receive signals to the channel estimator **230** and the receive signal converter **250** (S**310**).

The channel estimator **230** estimates the channel H_c based on the receive signals, converts the estimated channel H_c to

the real equivalent channel H, and applies the converted real equivalent channel H to the channel converter **240** (S**320**).

The channel converter **240** arranges the columns of the real equivalent channel H and decomposes the real equivalent channel H to the QR matrix using the MGS (S**330**). The channel converter **240** applies the matrix H used to arrange the columns of the real equivalent channel H to the receive signal converter **250**.

In the mean time, the receive signal converter **250** converts the receive signal fed from the receiving part **220** to the real equivalent receive signal r and arranges the columns of the real equivalent receive signal r in the same manner as the column arrangement of the real equivalent channel H. Next, the receive signal converter **250** generates and applies the converted receive signal to the detector **260** (S**340**).

The detector **260** detects the estimate of the transmit signal by executing the maximum likelihood decoding based on the matrix R fed from the channel converter **240** and the converted receive signal (S**350**).

The parallel/serial converter **270** serial-converts the detected estimate of the transmit signal, and the demodulator **280** acquires the original information data bits by demodulating the serial symbols (S**360**).

FIG. **4** is a block diagram of a receiver using the hard decision according to another exemplary embodiment of the present invention.

Unlike the detector **260** of FIG. **2**, a detector **260** of FIG. **4** further comprises first through fourth storages **262-1** through **262-4**, first through fourth hard decision parts **264-1** through **264-4**, and first through fourth candidate set parts **266-1** through **266-4**.

The first through fourth storages **262-1** through **262-4** store candidates for x_5, X_6, X_7 and x_8 respectively.

The first through fourth hard decision parts **264-1** through **264-4** decides x_1, x_2, x_3 and x_4 candidates corresponding to the x_5, x_6, x_7 and x_8 candidates stored to the first through fourth storages **262-1** through **262-4** respectively using the hard decision. The first through fourth hard decision parts **264-1** through **264-4** apply the decided candidate groups (x_1,x_5), (x_2, x_6), (x_3, x_7) and (x_4, x_8) to the candidate set parts **266-1** through **266-4** respectively.

The first through fourth candidate set parts **266-1** through **266-4** temporarily store the candidate groups fed from the first through fourth hard decision parts **264-1** through **264-4** and apply the candidate groups to the first through fourth estimate detectors **268-1** through **268-4**.

The first through fourth estimate detectors **268-1** through **268-4** determine the candidate group meeting Equation 10 among the candidate groups stored to the first through fourth candidate set parts **266-1** through **266-4** as the permutated estimate and detects the estimate of the transmit signal corresponding to the permutated estimate.

As such, since the candidate group is determined using the hard decision and the estimate is detected from the determined candidate group, the complexity of the detector can be drastically reduced to 0 ($4\Omega^{1/2}$).

FIG. **5** is a flowchart of a maximum likelihood decoding method using the hard decision at the detector **260** of FIG. **4**. Since the receiver of FIG. **4** receives the receive signals, generates the permutated channel R and the converted receive signal r_{perm}, serial-converts and modulates the symbols as explained in FIG. **3**, further description shall be omitted. The decoding method of the detector **260** is now illustrated.

The first through fourth hard decision parts **264-1** through **264-4** determine the real transmit signal candidate $x_{perm\,j}$ with respect to the imaginary transmit signal candidate $x_{perm\,j+4}$ stored to the first through fourth storages **262-1** through **262-4** using the hard decision (S**510**).

The first through fourth candidate set parts **266-1** through **266-4** temporarily store the imaginary transmit signal candidate and the real transmit signal candidate determined at the first through fourth hard decision parts **264-1** through **264-4** as the candidate group (S**520**).

The first through fourth estimate detectors **268-1** through **268-4** determines one of the candidate groups stored to the first through fourth candidate set parts **266-1** through **266-4** as the permutated estimate using the maximum likelihood decoding, and detect the estimate of the transmit signal corresponding to the permutated estimate (S**530**).

FIG. **6** is a table showing the complexity of the conventional decoding method and the exemplary embodiments of the present invention. In FIG. **6**, the number of the transmit antennas is four, Ω is the modulation order, C_A is the complexity of the real addition, and C_M is the complexity of the real multiplication. The multiplication complexity of the complex number is the sum of four-time real multiplication and two-time real addition, and the addition complexity of the complex number is equivalent to two-time real addition. The complexity of the norm and the square is equivalent to the multiplication complexity of the complex number.

As shown in FIG. **6**, in case of 16 QAM, the complexity according to one exemplary embodiment of the present invention is reduced to 1/14 compared to the conventional complexity, and the complexity according to another exemplary embodiment of the present invention is reduced to 1/73 compared to the conventional complexity. In case of 64 QAM, the complexity of one and another exemplary embodiments is reduced to 1/60 and 1/744 respectively. That is, the maximum likelihood complexity of the present invention can be drastically reduced in the higher-order QAM.

FIG. **7** is a graph showing the bit error rate of the conventional decoding method and the present decoding method. In FIG. **7**, the number of the transmit antennas is four. As one can see from FIG. **7**, the performance of the conventional decoding method is substantially the same as the performance of the present decoding method.

Therefore, with substantially the same performance as the conventional method, the present decoding method can drastically reduce the complexity.

While the MIMO mobile communication system using four transmit antennas has been illustrated by way of example, the decoding method of the present invention is applicable to a MIMO mobile communication systems using an even number of transmit antennas.

As set forth above, since the transmit signal candidates for the maximum likelihood decoding method are independent of each other, the complexity of the maximum likelihood decoding can be decreased. In addition, with the lowered complexity of the receiver, the power consumption for the decoding can be reduced and the high-speed data can be transmitted more easily in the actual mobile communication environment.

The foregoing exemplary embodiments and advantages are merely exemplary and are not to be construed as limiting the present invention. The present teaching can be readily applied to other types of apparatuses. Also, the description of the exemplary embodiments of the present invention is intended to be illustrative, and not to limit the scope of the claims, and many alternatives, modifications, and variations will be apparent to those skilled in the art.

What is claimed is:

1. A decoding apparatus comprising:
a channel estimator which estimates a real equivalent channel based on a coded signal;
a channel converter which decomposes the real equivalent channel to a unit matrix and a subchannel;
a receive signal converter which converts the coded signal to a real equivalent receive signal and converts the real equivalent receive signal to a converted receive signal based on the unit matrix; and
a detector which detects an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel,
wherein the channel converter rearranges columns of a real equivalent channel using an orthogonal matrix and converts the rearranged real equivalent channel to the unit matrix and the subchannel.

2. The decoding apparatus of claim 1, wherein the coded signal is encoded using a quasi-orthogonal space-time block code.

3. The decoding apparatus of claim 1, wherein the detector comprises:
a hard decision part which determines a transmit signal candidate group using a hard decision; and
an estimate detector which detects a transmit signal estimate from the transmit signal candidate group output from the hard decision part by performing the maximum likelihood decoding.

4. The decoding apparatus of claim 3, comprising:
a channel estimator which estimates a real equivalent channel based on a coded signal;
a channel converter which decomposes the real equivalent channel to a unit matrix and a subchannel;
a receive signal converter which converts the coded signal to a real equivalent receive signal and converts the real equivalent receive signal to a converted receive signal based on the unit matrix; and
a detector which detects an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel,
wherein the detector comprises:
a hard decision part which determines a transmit signal candidate group using a hard decision; and
an estimate detector which detects a transmit signal estimate from the transmit signal candidate group output from the hard decision part by performing the maximum likelihood decoding,
wherein the hard decision part determines a real transmit signal candidate as the transmit signal candidate group from an imaginary transmit signal candidate using the hard decision.

5. The decoding apparatus of claim 1, wherein the coded signal is transmitted over four transmit antennas.

6. The decoding apparatus of claim 1, wherein the channel converter converts the real equivalent channel to the unit matrix and the subchannel using a modified Gram-Schmidt (MGS).

7. The decoding apparatus of claim 1, wherein the subchannel is in an upper triangular matrix format.

8. The decoding apparatus of claim 1, wherein the detector detects the estimate corresponding to the transmit signal by independently decoding the converted receive signal corresponding to the coded signal.

9. A decoding method comprising:
estimating a real equivalent channel based on a coded signal;
decomposing the real equivalent channel to a unit matrix and a subchannel;
converting the coded signal to a real equivalent receive signal and converting the real equivalent receive signal to a converted receive signal based on the unit matrix; and
detecting an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel,
wherein the channel decomposing operation rearranges columns of a real equivalent channel using an orthogonal matrix and converts the rearranged real equivalent channel to the unit matrix and the subchannel.

10. The decoding method of claim 9, wherein the coded signal is encoded using a quasi-orthogonal space-time block code.

11. The decoding method of claim 9, wherein the estimate detecting operation comprises:
determining a transmit signal candidate group using a hard decision; and
detecting a transmit signal estimate from the transmit signal candidate group by performing the maximum likelihood decoding.

12. A decoding method comprising:
estimating a real equivalent channel based on a coded signal;
decomposing the real equivalent channel to a unit matrix and a subchannel;
converting the coded signal to a real equivalent receive signal and converting the real equivalent receive signal to a converted receive signal based on the unit matrix; and
detecting an estimate of a transmit signal by performing a maximum likelihood decoding using the converted receive signal and the subchannel, wherein the estimate detecting operation comprises:
determining a transmit signal candidate group using a hard decision; and
detecting a transmit signal estimate from the transmit signal candidate group by performing the maximum likelihood decoding, and
wherein the candidate group determining operation determines a real transmit signal candidate as the transmit signal candidate group from an imaginary transmit signal candidate using the hard decision.

13. The decoding method of claim 9, wherein the coded signal is transmitted over four transmit antennas.

14. The decoding method of claim 9, wherein the channel converting operation converts the real equivalent channel to the unit matrix and the subchannel using a modified Gram-Schmidt (MGS).

15. The decoding method of claim 9, wherein the subchannel is of an upper triangular matrix format.

16. The decoding method of claim 9, wherein the estimate detecting operation detects the estimate corresponding to the transmit signal by independently decoding the converted receive signal corresponding to the coded signal.

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